A novel application of a double convex-hemispherical lens configuration for a III-V tandem InGaP/GaAs/Ge multi-junction solar cell

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Abstract

Concentrator photovoltaics require solar trackers to maximize sunlight capture. However, solar trackers are expensive both in components and utility. In this study, the lens configuration was modified to eliminate the need for solar trackers, as well as improve power output. This configuration consisted of a double convex, hemispherical lens, and a Fresnel lens all positioned on top of the multi-junction solar cell. The double convex-hemispherical lens (DCX-HSL) setup was based on the Fresnel lens setup which is composed of a Fresnel lens placed on top of the multi-junction solar cell. To test the merits of the DCX-HSL setup, it was tested against a signal Fresnel lens concentrator over the course of one photoperiod. The results showed that there is a significant difference in the power output of the DCX-HSL to the Fresnel lens setup from 10:15 to 14:15. The improvement of the power output from 10:15 to 14:15 is due to the added convex lens and hemispherical lens that focuses more light to the solar cell.

Keywords: *three-lens system, concentrator photovoltaic, hemispherical lens, convex lens*

Introduction. The lenses concentrate the sun's rays to the solar cell. Photovoltaics (PV) systems are known to convert sunlight into electricity at an estimated amount of one sun (1368 W/m^2) under favorable weather conditions [1]. The manufacturing of PV systems is expensive due to the components used in the system. There are different kinds of PV systems, ranging from conventional PV to Concentrator PV (CPV). CPVs were developed to utilize concentrating lenses and mini-reflecting mirrors to increase the power efficiency of the device. The introduction of concentrator lenses and mirrors in a PV system increases the power output per unit cost. CPV technology is relatively new when compared to conventional PV systems, requiring further optimization and research in comparison to them. One such consideration is the dispersion of light caused by the concentrating lenses. This is due to the optical properties and design of the lens being used [2]. The angle of the CPV relative to the sun is an important factor in optimizing sunlight collection, and therefore power production [3]. To achieve maximum efficiency, the sun must be perpendicular to the CPV for the concentrated light to be focused unto the solar cell [1].

To improve the CPV's ability to concentrate light, there were various designs and modifications that have been investigated. One study involved the use of a compound convex lens set up to improve the concentration of light and the concentration ratio [3]. Additionally, Jing et al. [4] developed a cost-effective compound setup using a three-dimensional lens. The setup also increases the acceptance angle and improves the irradiance distribution. This increases the performance of the solar cell as sunlight is directed to the solar cell longer due to the increase in acceptance angle. If a three-lens system CPV with a convex lens and a three-dimensional lens or similar were added to a Fresnel lens-based CPV, then the modified CPV may gain both benefits from the two studies.

The lenses concentrate the sun's rays to the solar cells; thus, it produces more electrical energy per cell and decreases the need for several solar cells, making CPVs more efficient than PVs [5]. The drawback is the increase in the cost for each individual solar panel or module [6]. To further improve the CPV, studies by Jing et al. [4], Huang et al. [7], and Barrios et al. [3] attempted different designs and modifications to improve the collection efficiency of the lens system, conversion efficiency of the solar cell [8], and many more aspects. As a result of these different studies, cost-effective CPVs were developed with capabilities of the costlier variants.

The Fresnel lens has been the lens of interest in these studies due to its properties such as being lightweight, cost-efficient, and smaller in volume compared to other concentrating lenses [7]. Fresnel lenses were used as a circular spot concentrating lens, which increased the conversion efficiency of the solar cell from 6.4% to 7%.

This study aimed to design a three-lens system to improve the range of the acceptance angle and the overall power output of a Fresnel lens CPV. The three-lens setup is referred to as the double convex-hemispherical lens (DCX-HSL), which was the modified setup while the Fresnel lens setup was the control setup. It specifically aimed to:

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(i) measure the voltage and current of the DCX-HSL setup and the Fresnel lens setup; and

(ii) compute and compare the power output of the DCX-HSL setup and the Fresnel lens setup.

Methods. The software Ray Optics Simulation™ v1.0.0 was utilized to create a light ray diagram for the theoretical modeling of the DCX-HSL setup and the Fresnel lens setup. A diagram was created to simulate how the ray dispersion differs between the DCX-HSL setup and the Fresnel lens setup. The acceptance angles of the DCX-HSL setup and the Fresnel lens setup were theoretically modeled.

Assembly of the Fresnel lens setup. Figure 1 shows the structure of the Fresnel lens setup. The setup was composed of one 5 cm x 5 cm Fresnel lens with a focal point of 5 cm and a multi-junction solar cell. The Fresnel lens, which served as the primary lens in this setup, was situated 5 cm above the multi-junction solar cell.

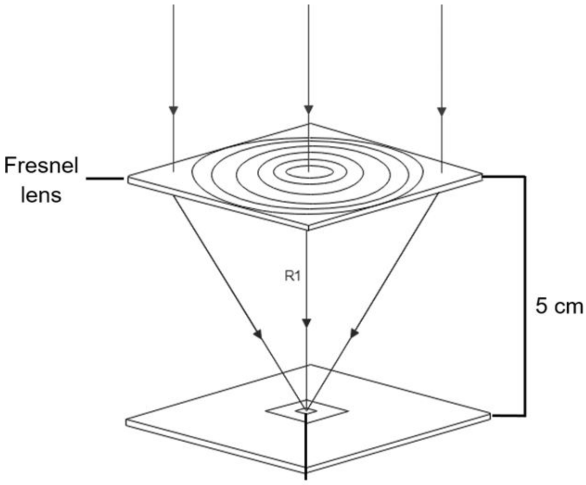

Figure 1. 3D image of the Fresnel lens setup.

Assembly of the DCX-HSL setup. A double convex lens and a hemispherical lens (HSL) with a radius of 2.5 cm and 0.5 cm, respectively, were attached to a Fresnel lens setup as shown in Figure 2. The hemispherical lens with a focal point of 0.5 cm was attached above the solar cell. The Fresnel lens was adjusted 5 cm above the hemispherical lens while the convex lens with a focal point of 10 cm was situated 5 cm above the Fresnel lens.

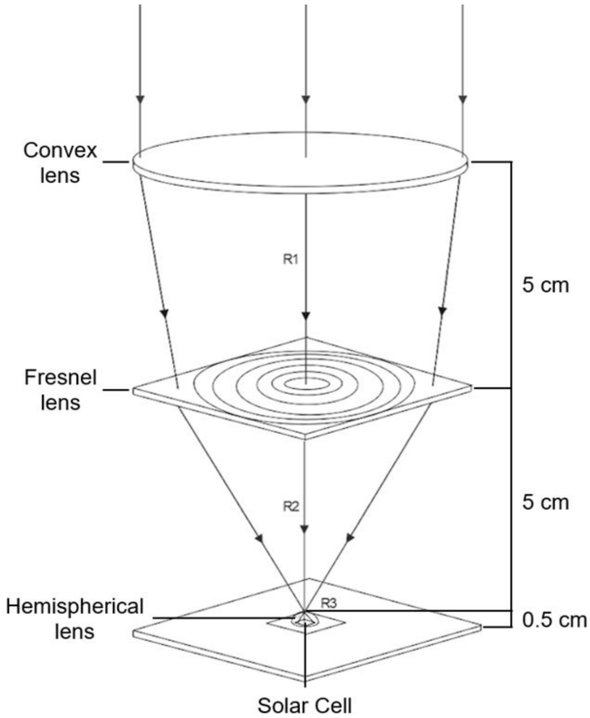

Figure 2. 3D image of the DCX-HSL lens setup.

The control setup consisted of a solar cell with a Fresnel lens functioning as its primary concentrator whereas the DCX-HSL setup was comprised of the same solar cell with convex, Fresnel, and hemispherical lenses acting as its primary, secondary, and tertiary concentrators respectively

Field testing of the Compound Fresnel-3D lens setup and Fresnel lens setup. The setups were tested on the rooftop of the Student Learning Resource Center Building located at Philippine Science High School - Western Visayas (10°45'10.7"N 122°35'15.8"E). The DCX-HSL setup and Fresnel lens setup were placed flat on a table and were adjusted to 0° with reference to the ground using a surface leveling application. Voltage, current, and solar irradiance were measured hourly with the time of data gathering recorded. A multimeter was used to measure the voltage and the current ,while a solar irradiance meter was used to measure the solar irradiance. Multiple trials were done until the value of three consecutive trials for each data had a difference of 0.001 volts for the voltage, 0.01 mA for the current, and 1 W/m^2 for the solar irradiance, which were the lowest precisions of the measuring devices used. The testing was conducted hourly from 6:15 am to 5:15 pm. Weather conditions such as the cloud cover were recorded as it may affect the data gathered.

Data Analysis. The hourly mean of the voltage and current was calculated and was used for the calculation of the hourly power output. The power output of the DCX-HSL setup and Fresnel lens setup was calculated using the formula

$$P = I \times V \tag{1}$$

where P is the calculated power output in watts, I is the measured current in amperes, and V is the measured voltage in volts. The values, however, of the power and current in this paper were expressed in milliwatts and milliamperes, consistent with the precision of the tools used.

For the statistical analysis, the Wilcoxon Signed Ranks Test was used to compare the power output of the DCX-HSL setup and the Fresnel lens setup.

Results and Discussion. The findings and discussion were separated into four parts: voltage and irradiance, current and irradiance, power and irradiance, and data analysis.

Voltage and Irradiance. The Double Convex-Hemispherical Lens (DCX-HSL) setup had a lower voltage output compared to the Fresnel lens throughout the photoperiod, except from 10:15 to 14:15 (midday) as shown in Figure 3. The lower output of the DCX-HSL setup may have been due to the refraction caused by the HSL. Sunlight during 6:15 to 8:15 and 15:15 to 17:15 can reach the solar cell of the Fresnel lens setup without going through the Fresnel lens. The DCX-HSL, on the other hand, has an HSL that may have refracted some sunlight away from the solar cell. During midday, it was expected for both setups to have the highest output but only the DCX-HSL setup reached its peak, while the Fresnel lens setup dropped. This may have been due to the offset of the sun and the acceptance angle of the two setups. The setups were stationary and adjusted to be perpendicular with respect to the horizon. Therefore, the conditions do not meet the requirements for the CPV to produce the maximum power. Since the DCX-HSL has a higher acceptance angle compared to the Fresnel lens setup, light rays were still redirected to the solar cell. This may be why the DCX-HSL setup increased in voltage and current output during midday, as expected while the Fresnel lens setup's dropped. The mean voltage of the DCX-HSL setup and Fresnel lens setup during 05:15 to 17:15 (whole day) was 2.1512 V and 2.1649 V, respectively.

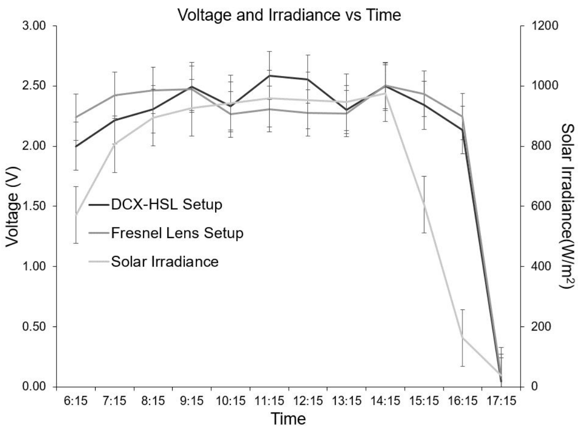

Figure 3. Average voltage of the DCX-HSL and Fresnel lens setup vs time during the photoperiod.

Current and Irradiance. The current of the two setups has a similar pattern to Figure 3 as shown in Figure 4. Since the current is proportional to the voltage, the current of the DCX-HSL setup is lower to the current of the Fresnel lens setup except during midday just like Figure 3. It is notable that during midday the Fresnel lens setup had a constant output. Other than the offset of the sun, this may also be due to the limit in the precision of the measuring tools. The same may be said when the two setups had a zero current output where they may have had an output between 0.01 mA and 0.00 mA. The mean current of the DCX-HSL in the whole day setup was 0.0242 mA while the Fresnel lens setup was 0.0142 mA.

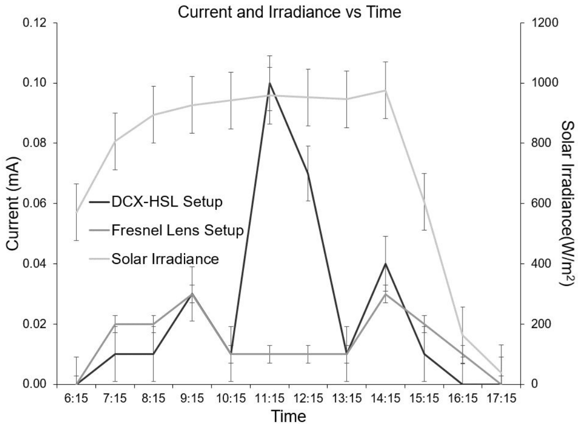

Figure 4. Average current of the DCX-HSL and Fresnel lens setup vs time during the photoperiod.

Power and Irradiance. After calculating the power output of the DCX-HSL and Fresnel lens setup, the results show a similar trend to that of Figures 3 and 4. The mean power output throughout the day of the DCX-HSL setup was 0.0606 mW, while for the Fresnel lens setup, it was 0.0341 mW.

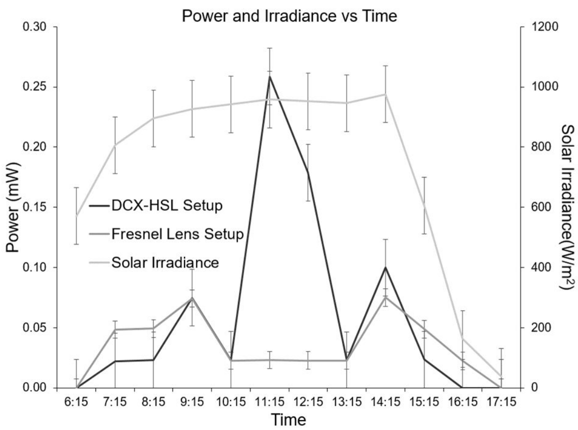

Figure 5. Average power output of the DCX-HSL and Fresnel lens setup vs time during the photoperiod.

The mean irradiance throughout the day was 732 W/m^2. Irradiance gradually increased until 11:15, upon which it gradually decreased. At 13:15 to 14:15, the irradiance had a slight increase before rapidly decreasing until 17:15.

The DCX-HSL setup yielded a higher power output than the Fresnel lens setup for both the whole day and midday by 77.65% and 251.05%, respectively.

Data Analysis. The p-value of the data was calculated using the Wilcoxon Signed Ranks Test with a confidence value (α) of 0.05 for a 95% confidence level. The test showed a significant difference from 10:15 to 14:15 (midday) in the output of the DCX-HSL setup and the Fresnel lens setup, as shown in Table 1. As for the whole photoperiod, there is no significant difference between the output of the DCX-HSL setup and the Fresnel lens setup.

Table 1. The p-value for the difference in the power outputs between the DCX-HSL and Fresnel setups at midday and the whole day.

Time of the day	Z	p-value Asymp. Sig. (2-tailed)
Midday	-2.023	0.043
Whole Day	-0.255	0.799

The addition of a convex lens as a primary lens and a hemispherical lens as another secondary lens in the optical system of a Fresnel lens setup increased its overall power output. The increase in power output was calculated to be 77.65% by the whole day while the calculated increase during midday was 251.05%. This may be due to the addition of lenses which increased the acceptance angle of the system [3].

At 10:15, cloud covers were observed; therefore, a lower output is expected for both setups. The power output of the DCX-HSL and Fresnel lens setup from 9:15 to 10:15 dropped from 0.0749 and 0.0742 to 0.0233 and 0.0226, respectively.

The data shows a similar trend to Barrios et al. [3] wherein the irradiance rose from 6:15 to 12:15, where the sun rises to its peak, resulting in an increase in the voltage and current output throughout the said duration. As the irradiance decreased from 13:15 to 17:15, the voltage and current output also decreased. Weather conditions may explain the similarities observed between the results of this study and of Barrios et al. [3]. Furthermore, cloud covers noted in the study caused a sudden decrease in the voltage and current output; resulting in a lower power output. The standard deviation of the power of the DCX-HSL setup was ±0.0815 whereas the Fresnel lens setup was ±0.0251. This shows a large standard deviation in the power of both setups. The large standard deviation may be caused by the intermittent cloud covers during the conduct of the data gathering.

Limitations. External factors such as the sudden cloud covers cannot be controlled during the data gathering. This may have affected the voltage and current output of the CPV. Precision in measurements was limited to the precision of the tools used. The schedule of the data gathering was affected by time constraints, thus, it was only performed in under one day.

Conclusion. It was determined that the power output of the CPV increased with the addition of a convex and hemispherical lens for the entire photoperiod. The DCX-HSL had a higher power output than that of the Fresnel lens setup. The DCX-HSL setup yielded a significant power output relative to the Fresnel setup from 10:15-14:15. The mean power output of the DCX-HSL setup and Fresnel lens setup during the photoperiod was 0.0606 mW and 0.0341 mW, respectively. Highest power output increase of DCX-HSL setup was recorded at midday at 251.05%, while on average, the DCX-HSL setup reported a 77.65% increase for the whole day. Although it is worth noting, that there is a large calculated standard deviation of the power for the DCX-HSL and the Fresnel lens setup. This shows similar results with Barrios et al. regarding the increase in power output and a significant difference during midday only.

Since the data gathering was conducted for only one day, the effects of the atmospheric condition were not minimized. Therefore, the results may vary during other days where the weather conditions are different. Further research regarding the three-lens CPV system should be done with at least a three day data gathering period for more accurate data. The type, design, or number of lenses may also be altered to learn its effects on the CPV.

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